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Estimating sediment delivery ratios using connectivity index and high-resolution digital elevation model at lower Snowy River area, Australia

Xihua Yang [a,b], John Young [a], Haijing Shi [c], Greg Chapman [a], Ian Pulsford [d], Cara Moore [d], Angela Gormley [b] and Richard Thackway [d]

[a] *NSW Government Department of Planning and Environment, Parramatta, NSW, Australia*
[b] *School of Life Sciences, University of Technology Sydney, Broadway, NSW, Australia*
[c] *Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi, China*
[d] *Fenner School of Environment and Society, Australian National University, Canberra, Australia*
Email: xihua.yang@environment.nsw.gov.au

Abstract: Understanding patterns of sediment transport and deposition in natural landscapes is critical in developing cost-effective mitigation measures to control soil erosion and protect water quality. Many physical based models are capable to assess spatio-temporal patterns in sediment dynamics, but difficult to be applied in wilderness areas with little field data. For the first time, the sediment connectivity index (IC) was applied to examine the sediment and connectivity patterns across a rugged landscape in the lower Snowy River area, Kosciuszko National Park, Australia. A high-resolution (2 m) digital elevation model (DEM) was used to derive a seven-class landform classification based on the fuzzy logic landform model (FLAG). Sediment and erosion models (SedAlp, RUSLE) were used to estimate the IC, erosion and sediment yield in a geographic information system (GIS) environment. Field work was carried out at 12 paired vegetation plot sites to measure fractional vegetation cover and slope parameters and take soil samples for laboratory analysis which were in turn used to validate the model estimation. Results show that IC has moderate to strong positive correlation with SDR which can be used to estimate the overall sediment budget across landscapes. The lower slopes in the landscape appear to have a higher sediment connectivity due to steep slopes and degraded vegetation condition caused by feral animal and human disturbances, while the valley has the lowest sediment connectivity on average due to better ecological restoration. Findings from this study can be used to locate and monitor the areas likely to generate high sediment yield and nutrient transport for developing ecological restoration, feral animal management and other catchment management measures. Compared to the empirical equations developed for specific areas, the IC based SDR estimation is generic thus it's applicable elsewhere.

Keywords: *Water erosion, nutrient loss, sediment yield, soil carbon, water quality, Kosciuszko National Park*

1. INTRODUCTION

The sediment delivery ratio (SDR) is defined as the ratio of sediment yield to gross erosion or the fraction of gross erosion (interill, rill, gully and stream erosion) that is expected to be delivered to a point of interest (Lane et al., 2017). SDR is commonly used in erosion and transport studies to describe the extent to which eroded soil (sediment) is removed or stored within a basin or a catchment. SDR can be affected by several factors including sediment source, soil properties (e.g., texture, erodibility), nearness to the mainstream, channel density, basin area, slope length, land use/land cover, and rainfall-runoff factors. Most of these variables are related to landforms (or geomorphology) which affect all erosion processes including sediment sources, transport and deposition (Xu et al., 2017).

The Index of Connectivity (IC) has been developed to represent the potential connectivity between the different parts of a watershed and a defined target (e.g., outlet, gully, creek, ephemeral stream, river, lake, dam), considering the topographic and land use conditions of the drainage area, flow path characteristics and flow accumulation along the route (Borselli et al., 2008). Due to the simple and clear calculation scheme, the IC and its modified versions have been widely applied to qualitatively estimate potential sediment connectivity and SDR between catchment components in different regions (e.g., Lopez-Vicente and Ben-Salem, 2019; Zanandrea et al., 2020; Zhao et al., 2020; Olsen et al., 2021; Zeng et al., 2023). So far, few studies have investigated connectivity on large basin scale due to the spatial heterogeneity of large areas and the presence of complex landforms and land uses (Wu et al., 2023). The IC concept has never been used in Australia for SDR and sediment yield related studies in a catchment scale.

In this study, we aimed to develop a practical means for determining the sediment budget across a hilly landscape using relatively easily obtained data and simple methods. The specific objectives were to: i) delineate landforms using a high-resolution DEM; ii) estimate SDR and sediment yield based on the IC concept; iii) assess SDR across various landforms in a catchment scale; and iv) analyse the impacts of land uses and management on sediment delivery ratios. Findings from this study may assist catchment managers to locate and monitor the areas with high sediment yield and nutrient transport and to develop cost-efficient ecological restoration and catchment management measures. This was the first attempt in Australia using the generic IC concept for SDR estimation, the methodology developed in this study is expected to be useful and applicable elsewhere.

2. METHODS AND MATERIALS

The Byadbo Wilderness Area is at the lower Snowy River valley within the southern section of Kosciuszko National Park adjacent to the border between NSW and Victoria. It is located approximately 420 kms from Sydney and 250 km from Canberra to the south, covering an area of approximately 600 square kilometres. This area was chosen for this study because i) there are six paired herbivore proof enclosure and grazed control plots have been maintained and monitored since 1984 as part of a longitudinal study of the impact of introduced herbivores on vegetation communities (Pulsford, 1991; Ward-Jones et al., 2019); ii) the area contains various hilly landforms, catchments and streams at various sizes; and iii) high resolution (2 m) DEM was available.

Datasets used in this study include a 2-m digital elevation model derived from Lidar data, seasonal fractional vegetation cover derived from Landsat satellite data, the recent land use map, soil attributes from soil and land information system (SALIS) and laboratory analysis, rainfall from Bureau of Meteorology stations.

SDR is ideally calculated from the measured sediment yield (SY) and gross erosion (GE) in a certain interval of time (such as monthly or annual):

$$SDR = SY/GE \tag{1}$$

where SY is the average sediment yield per unit of area in each period (Mg ha^{-1} time^{-1}); GE is the average gross erosion over the area of interest in a given period (Mg ha^{-1} time^{-1}). SDR is unitless with floating values ranging from 0 to 1.

The gross erosion rates (monthly and annual) for this study area were estimated based on revised universal soil loss equation (RUSLE) and the detailed methods are presented in our previous publications (Yang, 2014; Yang, 2015; Yang and Yu, 2015; Yang et al., 2017; Yang et al., 2023). In this study, the seasonal fractional cover derived from Landsat images (at 30 m spatial resolution) was used to estimate the cover and management (C) factor for the period 1988–2022.

The IC calculation includes two components: the downslope component (D_{dn}) and the upslope component (Dup). D_{dn} represents the probability of sediment to arrive at a sink through the flow path, considering flow length, local conditions, and slope gradient. D_{up} is the potential of downward movement of the upslope flow and sediment, depending on local conditions, slope and size of the drainage area. Then, IC is calculated as the logarithm of the relationship of D_{dn} and D_{up}:

$$D_{up} = C_{th} S_{th} \sqrt{A} \quad (2)$$

$$D_{dn} = \sum_i \frac{d_i}{C_{th,i} S_{th,i}} \quad (3)$$

$$IC_i = log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \quad (4)$$

$$SDR_i = \frac{SDR_{max}}{1+\exp\left(\frac{IC_0 - IC_i}{k}\right)} \quad (5)$$

where C_{th} is the average weighting factor (or threshold) of sediment transport impedance of the upslope drainage area reflecting the effect of cropping and management practices of the different land uses on the soil erosion rates, S_{th} is the average slope gradient of the upslope drainage area (m/m) representing the impact of slope on sediment connectivity and transport, A is the upslope drainage area (m^2), di is the length of the ith cell along the downslope path (m), IC_i is connectivity index value at the ith cell. The IC values are dimensionless [-∞, +∞] and it strongly depend on the computation target and pixel size, and at each pixel, different values can be obtained due to the index setup (Lopez-Vicente et al., 2021).

3. RESULTS AND DISCUSSION

The estimated annual erosion rates range from 0.7 to 2.7 Mg ha^{-1} yr^{-1}, with a mean of 1.5 Mg ha^{-1} yr^{-1} in the Pilot and Byadbo Wildness Areas. Higher erosion risk areas are mostly located in steep hillslopes or the steepest catchment areas in the western side of the Snowy River. These steep catchment areas often have smaller contributing area, thus the SDR values are higher than larger catchments. It has been explained by Boyce's theory (1975) that the value of the SDR decreases as the catchment area increases. In larger catchments there are more places to stop sediments between the source and deposition areas of the catchment.

The monthly erosion rates in the study area range from near zero to 0.8 Mg ha^{-1} m^{-1}, with a mean of 0.2 Mg ha^{-1} m^{-1}. The highest erosion rates are in summer (December to February) and lowest in winter (June to August). This is in good agreement with the estimation in the rest area of NSW (Yang, 2020). The seasonal variation in study area is not as great as in NSW. This might be due to the relatively higher vegetation cover, cooler temperature, and uniform landforms in this area.

Various terrain attributes have been produced from the 2-m DEM including slope, aspect, curvature, flow direction, stream network, stream order, contributing area. The landforms were derived from the DEM using the FLAG model (Summerell et al., 2004). These terrain attributes were further used to estimate IC and SDR on pixel basis across the study area. The estimated IC, SDR, gross erosion and sediment yield at the plot sites are listed on Table 1. The estimation was compared against the available measurements and results from an empirical model at the plot sites. There is no great variation in SDR values among the plot sites as the landforms and remote sensed vegetation covers (or IC) at the plot sites don't vary greatly.

The SDR was estimated across the study area. SDR values vary on different landforms, vegetation covers and hydrological soil groups. The SDR values near the stream networks are higher than the surrounding hillslopes. This result agrees in general with the findings in southern highlands (Wasson et al., 1998) which concluded that the total sediment flux and sediment yield of the catchment have been dominated by the stream network. However, sediment can be deposited into short term stores such as in-stream bars, benches, or islands. When floods occur sediment may move into storage on the floodplain with a longer residency time. The transfer zone in a river system includes sediment going in and out of storage as well as being transported from upstream. The results here only present the transport on the hillslope and rills, the in-stream storage and transport are not considered in this study. Figure 1 shows an example map of the estimated average sediment delivery ratio (SDR) at plot sites 1 and 2 in study area.

The highest sediment yield was estimated to occur on lower slopes (LF4, 0.68 Mg ha^{-1} yr^{-1}), and valleys (LF7 have the lowest sediment yields (< 0.1 Mg ha^{-1} yr^{-1}). The results indicate that sediment is deposited on hillslopes, especially on lower slopes, during the transport process, little was delivered to valley and depositions.

Table 1. The estimated IC, SDR and sediment yield at plot sites and the outlets plot sites

PLOT ID	Long	Lat	Elevation (m)	Slope (%)	Length (m)	LS	Land form	IC	SDR	Erosion	SY (Mg ha^{-1} yr^{-1})
1	148	-37	305	57	63	13.3	LF3	-1.35	0.10	1.87	0.19
2	148	-37	296	43	73	11.2	LF3	-1.61	0.10	1.78	0.19
4	148	-37	347	42	123	14.2	LF5	-2.36	0.10	2.96	0.31
5	148	-37	334	48	33	7.4	LF7	-2.02	0.11	2.75	0.29
6	148	-37	325	32	23	4.9	LF6	-2.35	0.10	2.75	0.28
11	148	-37	352	47	48	9.6	LF2	-2.67	0.10	3.35	0.34
12	148	-37	336	38	98	10.7	LF3	-2.84	0.10	3.73	0.38
13	148	-37	351	41	4	2.4	LF3	-2.84	0.10	3.05	0.31
14	148	-37	350	45	18	5.7	LF3	-2.70	0.10	4.09	0.42
15	148	-37	343	39	73	10.2	LF4	-2.43	0.10	1.77	0.18

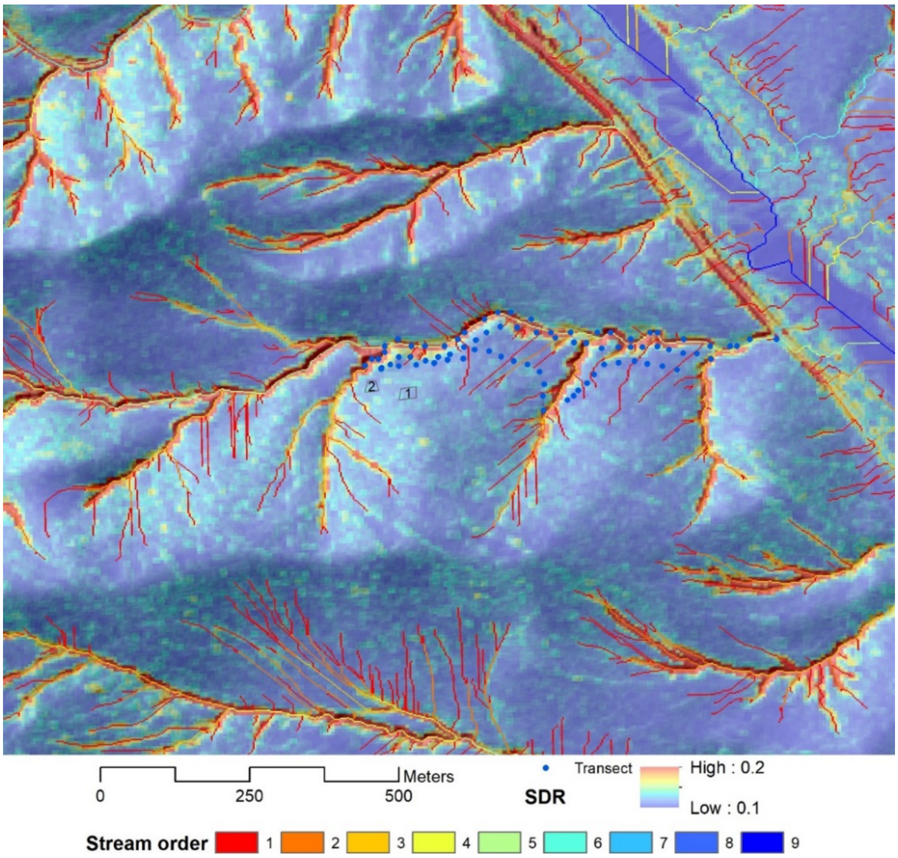

Figure 1. An example map of the estimated average sediment delivery ratio (SDR) near plot sites 1 and 2 in the study area

4. CONCLUSION

In this study, we applied a novel approach to estimate SDR and sediment yield across the study area. A seven-class landform system was delineated using a high-resolution DEM (2 m) and the FLAG model. The IC concept was used to estimate SDR, and sediment yield the first time in Australia. The estimated fractional vegetation, gross erosion, SDR and sediment yield were assessed at the 6 paired plot sites across the study area. The paired sites were observed and compared to assess the impacts of vegetation and terrains on SDR and sediment yield.

Our study re-emphasized the importance of landscape in SDR, and sediment yield as pointed out in a similar study in Australia (Smith, 2008) in which it states that landscape characteristics may often override good management practice and therefore in order to reduce sediment and nutrient loss farms must be designed and managed according to landscape features. SDR and sediment yield studies need to be carried out on a landscape scale rather than point scale.

Results from this study show that IC has moderate to strong positive correlation with SDR which can be used to estimate the overall sediment budget across landscapes. The lower slopes in the landscape appear to have a higher sediment connectivity due to degraded vegetation and steep slopes, while the valley has the lowest sediment connectivity on average due to better ecological restoration. Findings from this study can be used to locate and monitor the areas with high sediment yield and nutrient transport for developing cost-efficient ecological restoration and catchment management measures.

In future studies, the estimation of fractional vegetation cover needs to be improved using higher resolution satellite images (e.g., Planet or UAV). Understory vegetation cover also needs to be considered in erosion and sediment budget modelling. With available future climate projections (such as NARCliM 2.0), it’s possible to predict the future changes in erosion risk and sediment yield at a catchment or a region scale for climate adaptation and land use planning.

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